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Large-scale sedimentation on the glacier-influenced Polar North Atlantic margins: Long-range side-scan sonar evidence

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Abstract: Long-range side-scan sonar (GLORIA) imagery of over 600,000 km^2 of the Polar North Atlantic provides a large-scale view of sedimentation patterns on this glacier-influenced continental margin. High-latitude margins are influenced strongly by glacial history and ice dynamics and, linked to this, the rate of sediment supply. Extensive glacial fans (up to 350,000 km^3) were built up from stacked series of large debris flows transferring sediment down the continental slope. The fans were linked with high debris inputs from Quaternary glaciers at the mouths of cross-shelf troughs and deep fjords. Where ice was slower-moving, but still extended to the shelf break, large-scale slide deposits are observed. Where ice failed to cross the continental shelf during full glacials, the continental slope was sediment starved and submarine channels and smaller slides developed. A simple model for large-scale sedimentation on the glaciated continental margins of the Polar North Atlantic is presented.

Introduction

Glacier ice began to build up in high northern latitudes 5-10 M yr ago. However, a major increase in ice-rafted debris on the Norwegian margin from about 2.6 M yr ago indicates that large ice masses reached sea level at this time and began to input large numbers of icebergs to the continental margins of the Polar North Atlantic [*Jansen and Sjøholm,* 1991; *Larsen et al.*, 1994]. A series of 2 to 4 km-thick sedimentary wedges or fans was deposited [*Vorren et al.*, 1991], and major slope failures formed huge submarine slides [*Bugge et al.*, 1988]. This paper has two aims: (i) to use long-range side-scan sonar and associated seismic evidence to examine the sedimentary architecture and processes on the glacier-influenced passive continental margins of the Polar North Atlantic; and (ii) to present a simple model of sedimentation on this glaciated margin, where the distribution and dynamics of ice and the rate of sediment input are key controls.

Studies of large-scale sedimentation on the Polar North Atlantic margins took place during a 41 day cruise of RRS *James Clark Ross* (1994) and a 40 day cruise of RV *Livonia* (1992) [*Mienert et al.*, 1993]. About 530,000 km^2 of the continental slope and deep ocean floor was mapped (Fig. 1) using a long-range side-scan sonar system, GLORIA (Geological Long Range Inclined Asdic). GLORIA operates at 6.5 kHz with a swath width of about 25 km, a range resolution of 50 m and azimuth resolution of 50-600 m (depending on range). GLORIA data were also acquired on an earlier cruise to the Norwegian continental margin [*Kenyon*, 1987], giving a total of 625,000 km^2 of GLORIA data from the Polar North Atlantic.

This imagery is augmented by two types of acoustic data. First, a 3.5 kHz sub-bottom profiler provided high resolution stratigraphic data to depths of 10-60 m on 11,000 km of track acquired in 1994. Secondly, over 12,000 km of deeper penetration seismic records are also available from earlier studies on the Norwegian and, to a lesser extent, the Greenland continental margins [e.g. *Vorren et al.*, 1991; *Laberg and Vorren*, 1995; *Vanneste et al.*, 1995].

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Large-Scale Sedimentary Features

Several major sedimentary zones are mapped from the geophysical datasets (Fig. 1): extensive submarine fans; large slide complexes; and deep-sea channels and associated sandy channel-mouth lobes. Acoustically well-stratified hemipelagic sediments are also present in low energy environments distal to the shelf break, and provide a debris veneer in most areas during interglacials. Some small canyon- and gully-fed slide systems are also found near the shelf break.

Major Submarine Fans

Submarine fans are major constructional features around the Polar North Atlantic margins (Fig. 1). Several fan systems were imaged during our surveys. These included: (a) the Bear Island, Storfjorden, and Isfjorden fans on the continental margin of the Barents Sea and west of Svalbard, and (b) the Scoresby Sund Fan off East Greenland (Fig. 1). The largest is the Bear Island Fan (c. 350,000 km^3) which has a drainage area covering much of the western Barents Sea (c. 500,000 km^2) [*Vorren et al.*, 1991]. This fan is similar, in volume and rate of sediment input, to large lower latitude deep-sea fans, such as the Amazon and Mississippi fans, which have also built up over the last few million years [*Barnes and Normark*, 1985]. However, the estimated drainage area of these huge low latitude fans is 5-10 times greater than that of the Bear Island Fan [*Milliman and Meade*, 1983; *Vorren et al.*, 1991], demonstrating the efficient erosion and sediment transfer in high latitudes in response to the repeated growth and decay of Late Cenozoic ice sheets. This contrast with lower latitudes is accentuated further because ice is present at the shelf break for only a relatively small part of each glacial cycle.

Each of these major fans shows significant debris-flow activity (Fig. 1a-b, h). The morphology and architecture of the Bear Island Fan illustrates the nature of sedimentation on these glacier-influenced fans (Fig. 1). Between Bear Island

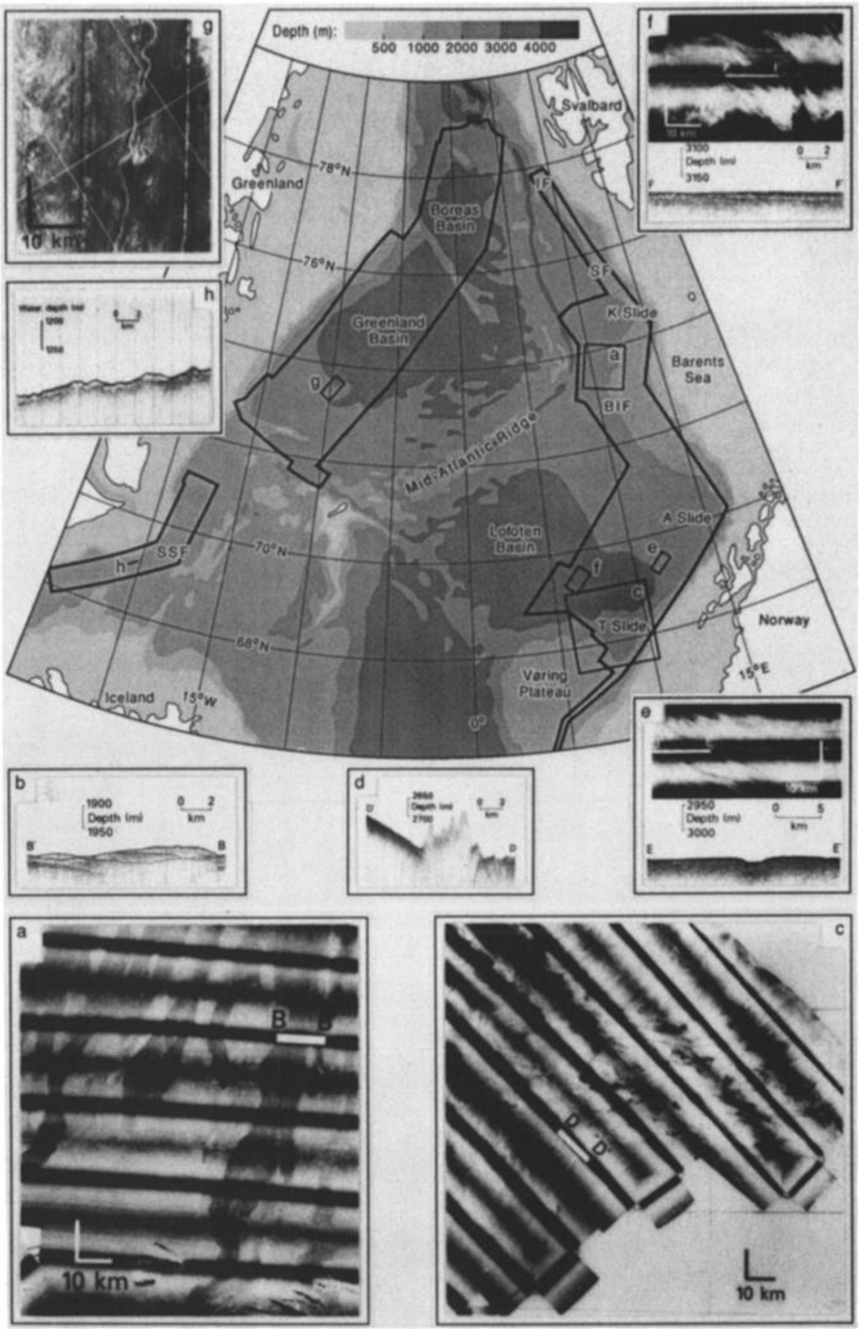

Figure 1. Map of the Polar North Atlantic between 66 and 80°N. Bathymetric contours at 1000 m intervals, plus the 500 m contour indicating the shelf break. Areas imaged by GLORIA are boxed. Eight extracts of GLORIA imagery and 3.5 kHz record are inset and are located on the main map. (a) A series of debris flow deposits on the Bear Island Fan (BIF) are seen as weaker backscatter (darker tones) on a GLORIA mosaic. (b) 3.5 kHz record showing the stacking of individual debris flow deposits. (c) GLORIA mosaic of the Traenadjupet Slide (T Slide). (d) 3.5 kHz record of blocky area on the Traenadjupet Slide at the foot of the Vøring Plateau slope. (e) GLORIA and 3.5 kHz records from a submarine channel, 15 m deep and 2.5 km wide, with slight braiding pattern, leading to the Lofoten Basin. (f) GLORIA and 3.5 kHz records showing areas of high backscatter and poor penetration of the sea floor beyond the terminus of the submarine channel in (e). (g) GLORIA mosaic of major submarine channels in the huge Greenland Basin. (h) 3.5 kHz record from a typical strike line across the Scoresby Sund Fan (SSF) showing debris flow deposits. SF is Storfjorden Fan, IF is Isfjorden Fan, A Slide is Andøya Slide and K Slide is Kveithola Slide.

and north Norway, there is a cross-shelf trough about 150 km wide and 500 m deep at its mouth, and the fan extends about 450 km out beyond the shelf break into the Lofoten Basin (Fig. 1). On the northern part of the fan there is a series of debris lobes [*Vogt et al.*, 1993; *Laberg and Vorren*, 1995] (Fig. 1a-b). The low-backscatter lobes are very long (up to about 150 km) and narrow (average widths about 7 km). They radiate out from the top of the fan and usually extend to near its base with mean volumes of about 10-20 km^3. The debris lobes are relatively transparent on 3.5 kHz profiles, and the underlying reflectors are easily seen (Fig. 1b). There is a similar pattern of debris-flow lobes identified on acoustic profiles from the other fan systems on the Polar North Atlantic margins (e.g. Fig. 1h), but the GLORIA sonographs of these areas lack the high acoustic contrast of Figure 1a.

Uniform lobe composition down the entire fan (100-200 km) suggests that the initial composition of failed sediments remains intact, with little sorting during transport. This is supported through core analysis, which shows a homogeneous diamicton with no indications of sorting along the slide body [*Laberg and Vorren*, 1995]. The few radiocarbon dates available from the debris lobes indicate that sediment build-up near the shelf edge, and its failure, took place when an ice sheet was last located at the shelf break, about 15-20,000 years ago [*Laberg and Vorren*, 1995]. The flows may be triggered by small tectonically-induced earthquakes associated with ice loading of the shelf [*Kvamme and Hansen*, 1989], by build-up of excess pore pressure due to rapid sedimentation, and/or by oversteepening of the sediment pile.

Large-Scale Slides and Deep-Sea Channels

In inter-fan areas on the eastern Polar North Atlantic margins, where large mass wasting features were first mapped by *Damuth* [1978] from 3.5 kHz records, three relatively large slides occur; the Traenadjupet, Andøya and Kveithola slide complexes (Fig. 1). There is also a large slide on the Bear Island Fan itself [*Laberg and Vorren*, 1993]. The Traenadjupet and Andøya slides each cover areas of 8-12,000 km^2, and have similarities with the huge Storegga slides south of the Vøring Plateau [*Bugge et al.*, 1988]. The slides originate in headwalls on the upper slope [*Kenyon*, 1987]. They appear as patterns of high backscatter on side-scan records (Fig. 1c), and are mainly erosional in their upper reaches and depositional downslope. Large areas of these deposits comprise blocks up to several kilometers wide with relief up to about 100 m (Fig. 1c-d). No large slides have been mapped off the East Greenland margin from 68-79°N [*Mienert et al.*, 1993].

GLORIA investigations on the Northeast Greenland margin showed that the Greenland Basin is dominated by four branching submarine channels of over 100 km in length (Fig. 1g) [*Mienert et al.*, 1993]. By contrast, few submarine channel systems have been imaged on the eastern margin of the Polar North Atlantic. A single major channel system (Fig. 1e) is located in the axis of the deep embayment south of the Bear Island Fan leading to the Lofoten Basin (Fig. 1). Its depth increases downslope to about 30 m. Its width, which is about 3 km, increases greatly where it reaches the basin plain. The fairly flat area beyond the channel has discontinuous bedding and relatively poor 3.5 kHz penetration (Fig. 1f). By analogy with similar areas beyond the mouths of other deep-sea channels, this is interpreted as a sandy channel-mouth lobe [*Kenyon and Millington*, 1995]. The channel system may be cut by cascading dense cold water from the Barents Shelf, formed by brine rejection during sea-ice formation [*Midttum*, 1985], or by turbidity currents generated by debris flows.

Large-Scale Sedimentation and Ice Dynamics

The Polar North Atlantic margins demonstrate a range of large-scale sedimentary settings influenced strongly by glacial history and ice dynamics. These factors, in turn, influence the rate of sediment supply. The Greenland Ice Sheet has shown relatively minor ice terminus fluctuations between recent glacials and interglacials, and has remained well inside the continental shelf break even during Late Weichselian full glacial conditions [*Dowdeswell et al.*, 1994]. North of the Scoresby Sund fjord and fan system, the continental shelf widens from <100 km to >200 km. Only limited quantities of sediment are transported to the continental slope, and submarine channel systems with minor slides are characteristic of the huge, abyssal Greenland Basin off the sediment-starved margin above 72°N [*Mienert et al.*, 1993].

On the eastern margin, by contrast, two different sets of sedimentary features are common on GLORIA records. The first are major deep-sea fans, developed at the mouths of cross-shelf troughs (Bear Island and Storfjorden fans) and major fjord systems (Isfjorden Fan) (Fig. 1). These topographic settings are associated in full glacials with strongly convergent ice flow and, hence, fast-flowing ice streams and outlet glaciers similar to those of the modern Antarctic and Greenland ice sheets. These ice streams can be on the order of 100 km across and are likely to be major sources of icebergs and of enhanced sediment flux, linked to velocities of up to several kilometers per year [*Dowdeswell et al.*, 1992]. Seismic evidence suggests that similar ice masses advanced to the continental shelf of central East Greenland and to the shelf break off troughs and large fjords in the Barents Sea in full

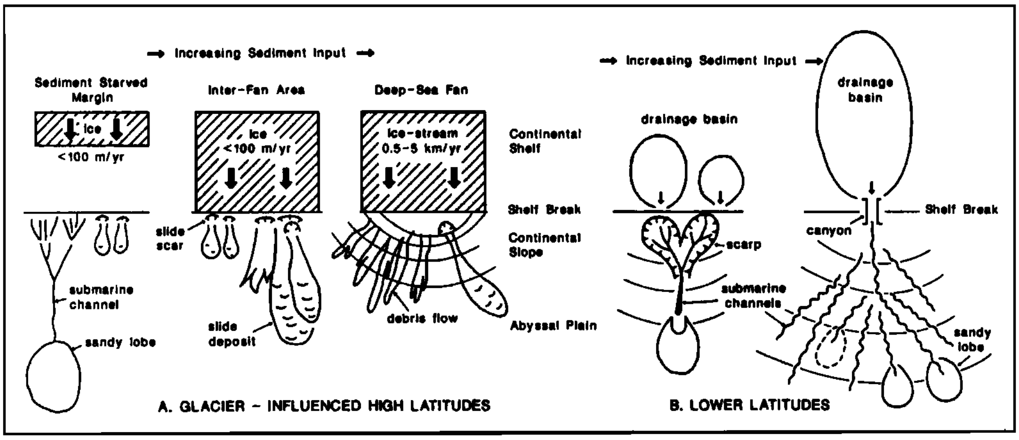

Figure 2. Conceptual model of sedimentation on glacier-influenced continental margins compared with lower latitude margins unaffected by ice. (a) Glaciated margins, showing variations in margin form and downslope sediment transfer linked to the ice dynamics and the rate of sediment delivery to the slope. (b) Fan systems at lower latitudes, characterized by channelized sediment transfer. The main control is the rate and volume of sediment input, with a continuum from high to low input fans.

glacials [*Dowdeswell et al.*, 1994; *Laberg and Vorren*, 1995]. Numerical models of the Quaternary ice sheets on the Barents Sea and Svalbard also predict that preferential flow will take place in major cross-shelf troughs due to convergent ice flow [*Siegert and Dowdeswell*, 1995]. Shelf sediments, mainly of glacimarine origin, are likely to be overrun and reworked during glacier advances through the shelf-troughs and fjords, and brought to the shelf edge beneath the ice sheet, probably as a deforming till-layer beneath relatively rapidly flowing ice streams [*Alley et al.*, 1989].

The second set of sedimentary features are inter-fan regions characterized by slower moving ice. The ice still reaches the shelf break and, consequently, sediment flux is higher than in Northeast Greenland. These regions exhibit: (a) a series of very large submarine slides (Fig. 1c-d), and (b) a few channel systems (Fig. 1e), less well-developed than the large systems on the sediment-starved Northeast Greenland margin (Fig. 1g).

A Model for Sedimentation on the Glaciated Polar North Atlantic Margins

We propose a conceptual model for large-scale sedimentation on the glaciated passive continental margins of the Polar North Atlantic, based on GLORIA imagery, seismic data and models of former ice-sheet behaviour (Fig. 2). Key model parameters are the degree to which glaciers extend across the continental shelf, and the rate of ice flow with its consequences for the rate of sediment delivery. The high rate of delivery at the mouth of fast-flowing outlet glaciers, associated with cross-shelf troughs and major fjords, produces large glacial fans (e.g. Bear Island, Storfjorden, and Scoresby Sund fans; (Fig. 1a-b). Where ice is slower-moving, but still extends to the shelf break, large-scale slide deposits form (e.g. Andøya and Traenadjupet slides; Fig. 1c-d). Wherever ice masses reach the shelf edge, sediments are delivered directly to the upper slope from beneath ice along a relatively long line source, of tens to hundreds of kilometers. If ice fails to cross the shelf during full glacial conditions, the slope remains sediment starved as it often is during interglacial and interstadials, and submarine channels and smaller slides are found; as in the extensive Greenland Basin offshore of the wide shelf of Northeast Greenland (Fig. 1g) [*Mienert et al.*, 1993].

The distinctive high latitude fans around the passive continental margins of the Polar North Atlantic, where sediment supply from fast-flowing ice is high and debris flows provide a major mechanism for build-up, appear different in both plan and in three-dimensional architecture from many lower latitude fans with extensive sinuous submarine channel-levee systems draining non-glaciated basins (Fig. 2).

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